Single Event Upsets in the Dual-Port-Board SRAMs of the MPTB Experiment

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Abstract

The in-flight data of SEUs in the devices of panels B and C of the MPTB experiments are presented. Ground test data for M65656 are used to calculate the SEU rates in this device using the calculated flux of ions along the orbit. The models used are CREME96, simple expressions derived here, and the figure of merit model. A very good agreement is found between these calculations and the observed rates.

I. Introduction

Panels B and C of the Microelectronics and Photonics Test Bed (MPTB) experiment each includes a 'Dual Port SRAM' board (boards B and C respectively). Each board houses four Matra M65656 32k×8 SRAMs, four IDT 7006 16k×8 dual port SRAMs, and four IDT 70V25 8k×16 dual port SRAMs. The experiments include dosimetry, propagation delay, threshold voltages, and currents, however, we will report here only on the single event upset (SEU) measurements.

First we will present the SEU results and show their locations in space. Then we will review the available ground test data for these chips which will be used to calculate the expected SEU rates. The expected rates will then be compared with the measured rates.

II. Inflight SEU Results

A. Locations of SEUs.

The data used in this analysis were from nearly one year of operation of the MPTB experiment. The orbits included are #267 (21 March 1998) to #987 (14 March 1999), altogether 721 revolutions. The symbols on Figure 1 show the location of all SEUs that occurred on board B (a very similar figure is obtained for board C). The location of each event is found by using its known time and performing a linear interpolation between the reported ephemeral points. The satellite orbit track for one day (two revolutions) is also shown in the figure as a dashed line. In the above duration of operation, the orbit deviated only little from this track. It has an inclination of 63.6°, a perigee of ~1220 km, an apogee of ~39200 km, and a period of 11.96 hours. The two perigee locations are at a latitude of −63.6° with longitudes of −97.55° and +82.45°.

Two kinds of high SEU locations are apparent in Figure 1. The first occurs near the equator where the satellite passes through the Van Allen proton belts. This is seen as four regions of large numbers of SEUs. Please note that the region east of South America is larger than the other three. It starts already at latitude of about -40° and altitude of about 2500 km (when the satellite is northbound) whereas the others extend south only to a latitude of about -20°. This is compatible with the contours of the proton belt at altitude of 3000 km [1], which are distorted due to the South Atlantic Anomaly. It is also in good agreement with the proton flux measurements of CREDO-3 on board of the MPTB satellite [2].

The second region is at latitudes >25° where the satellite is exposed to higher levels of galactic cosmic rays (GCR). The number of SEUs appears to be high but we will show later that this is because the satellite spends most of its orbital time at those latitudes due to the slow apogee passes. When the orbital time is taken into consideration, the actual rate is low relative to the rates in the proton regions. It is interesting to note that there are a few events during the short perigee passes (latitude >50°S) from exposure to heavy ions entering over the poles near Antarctica.

Figure 2 plots the altitude and latitude of the locations of the SEUs. As with Figure 1, it shows the two regions where large numbers of SEUs occur. Note the small difference between the up-going and down-going parts of the orbit.

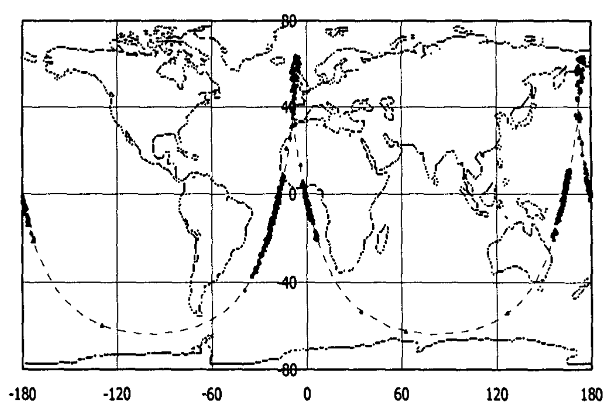

Fig. 1. The triangles show all SEUs in board B for a year (21 March 1998 to 14 March 1999). The dashed line shows the orbit (going eastward) of two consecutive revolutions. The perigees are at the southern-most points. Note that the region of SEUs east of South America extends to lower latitudes (and altitudes).

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B. Data Processing

The first phase in processing the telemetry files was to screen out anomalous events that were not actual SEUs. The devices are arranged on the board with 16 bits in a word. For the SEU experiments, all data loaded to even addresses were hexadecimal 5a5a and to odd addresses hexadecimal a5a5. This helped screening out data lines of other experiments, which used different input data. In the data read-out scheme, each error was detected many times before being reset. These were counted as one SEU. To decrease 'noise' we looked only for one bit flip in a word. The detected multiple-upsets were all double events in IDT 7006 occurring in adjacent addresses with the same upset bit.

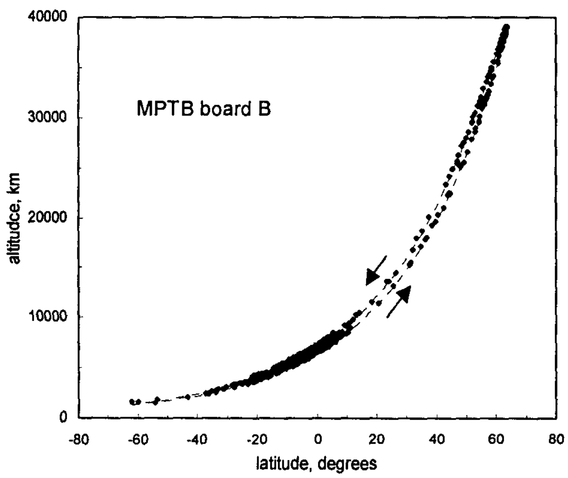


Fig. 2. Locations of all SEUs in board B in altitude *vs* latitude coordinates. The dashed line represents one revolution with the arrows showing the direction of the satellite in each half cycle.

Not all revolutions had well documented files. For the 721 revolutions, there were 538 files for board B with 516 SEUs (plotted in Figure 1) and 602 files with 396 SEUs for board C. For these revolutions, there is on the average one SEU per revolution for board B and only 2/3 of that number for board C (though the boards are built equally). Table 1 summarizes the total SEU counts for each device type. The higher sensitivity of the 7006 to SEUs when programmed to "0s" was also observed in ground experiments. Also interesting is the observation that the even addresses of the 70V25 experienced 23 "0-to-1" upsets and 10 "1-to-0" whereas the odd addresses experienced 10 "0-to-1" upsets and 35 "1-to-0". This appears to be within statistical error until data from the ground experiment are examined. In the thousands of upsets measured in proton beam exposures, this phenomenon was very pronounced.

C. SEU Rates Along the Orbit

The screened data were used to calculate upset rates as a function of altitude and dipole shell parameter, L. Here we will present the results for the M65656 for which we have almost complete ground test data.

Table 1: Total number of SEUs in boards B and C for orbits #267 (21 March 1998) to #987 (14 March 1999). Double events are identified as two events occurring in the same scan in the same bit and neighboring bytes.

Device Type	# of SEUs	# of Doubles	% "1-to-0"	% "0-to-1"
M65656	641	0	49	51
7006	193	5	35	65
70V25	78	0	59	41

Due to the nature of the orbit, the altitude is a symmetric function of time with time reversal occurring at perigee or apogee. The altitude can thus serve as a simple means to find the time of the upset within a single revolution instead of using the ephemeral files.

All 338 SEUs on the M65656 board B are plotted in Figure 3 in an altitude *vs* time chart. The horizontal density of the points gives the rate at each time and altitude. The inset magnifies the altitude regions below 10,000 km to show the high rate in the proton belt and the sharp cutoff at ~10,000 km.

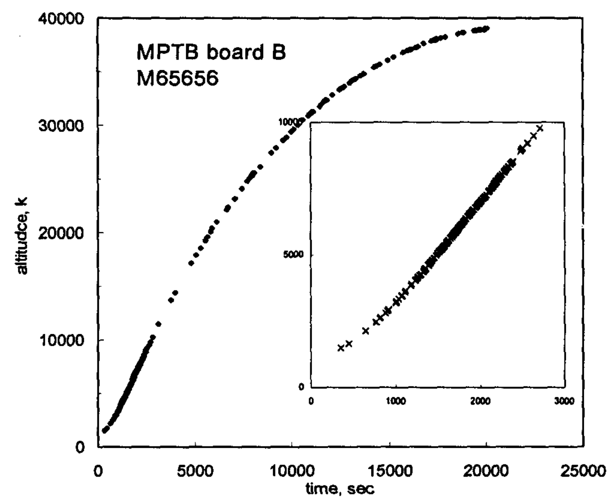


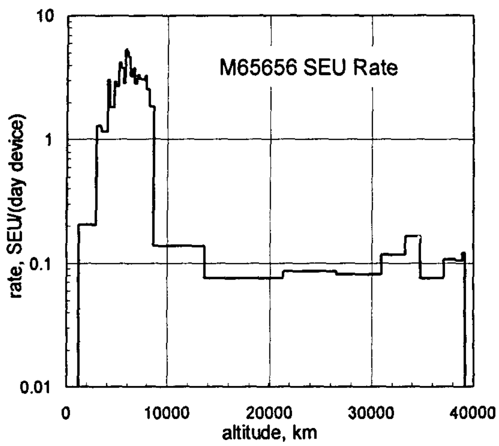
Fig. 3. The events of M65656 in board B in altitude *vs* time (from the last perigee or to next perigee, thus the time scale is for half a revolution). The inset enlarges the scales for the proton belt.

Figure 4 plots the SEU rate R as a function of altitude. It is calculated by finding the time interval Δt in Figure 3 of 20 consecutive events at a given altitude. Since the events are from 538 files i.e. 1076 half revolutions, $R = 20/1076\Delta t$.

The average rate of the two boards for all well documented revolutions was calculated and found to be 0.282 events per M65656 device per day. The SEU rate below 10,000 km is 0.2 upsets/device-day. These upsets are mainly caused by protons in the belts. The much lower rate of 0.082 SEUs/device-day at altitudes greater than 10,000 km is mainly due to heavy ions. These results are displayed in Table 2.

Since the proton flux is better determined by the L-shell parameter than by the altitude, we have plotted measured

M65656 SEU rate as a function of L in Figure 5. The peak SEU rate at L=1.8 is expected because this is the region of the



highest proton fluxes for the MPTB orbit. Note that the minimum L for the orbit is ~1.8.

Fig. 4. The rate of events in M65656 in boards B and C are given as a function of altitude.

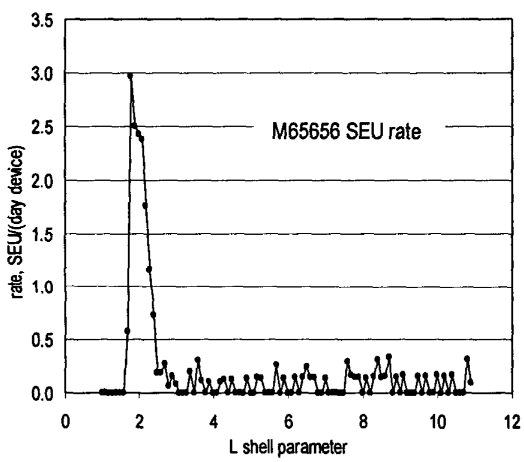


Fig. 5. The rate of events in M65656 in boards B and C as a function of the L-shell parameter.

D. Fluctuations in the SEU Rates

All the above analysis was done for the orbits up to #987 (14 March 1999, day 440 from 1-1-1998). With further SEU data being downloaded we found no major changes in the SEU behavior and the above analysis remains the same. Our data base was updated to orbit #1303 of August 18, 1999. To find the changes in the rates along the whole period from the first revolution probed (on 21 March 1998) to that date we plot in Figure 6 the number of accumulated SEUs as a function of the time (in days) from the starting of the year 1998. It is done separately for each kind of device (eight parts for each kind). We have to keep in mind that 20% of the telemetry files are missing which changes the slopes of the line and incorporates unreal fluctuations. When correcting for this factor the slopes represent rates of 0.275, 0.94, and 0.033 SEUs per day for M65656, IDT 7006 and IDT 70V25 respectively. The value for M65656 is very close to the above value of 0.282 per day. For the detailed analysis we use the latter value.

The fluctuations in the rates seem to be within statistical error. No sign of a solar flare was detected. Also we stopped detecting SEU in the IDT 70V25 devices after revolution #1104 (11 May 1999).

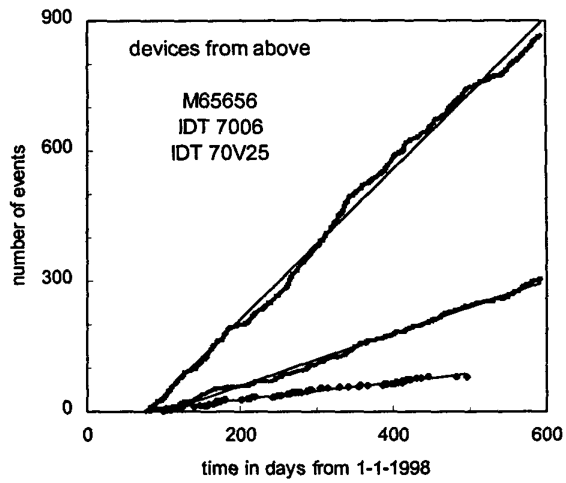
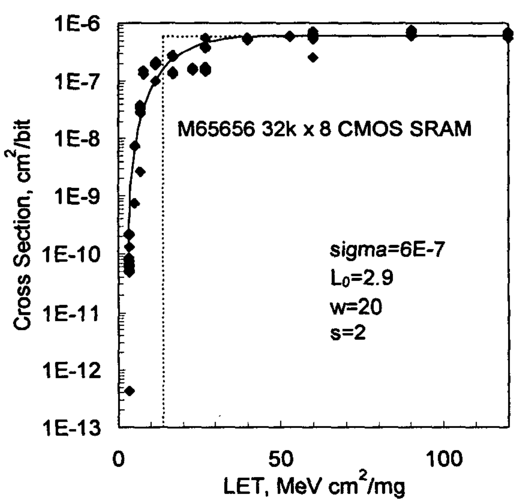


Fig. 6. The accumulated number of events as a function of time for the three kinds of devices. The slope gives the SEU rate as explained in the text.

III. Ground Test Data

We have tested all devices (of the flight lot) with low



energy protons but only the M65656 using heavy ions. The heavy ion ground test results for this device are given in Figures 7 and 8.

Fig. 7. The heavy ion cross section σ(LET) for M65656. The data were fitted by a Weibull function with limiting cross section

$\sigma_L=6\times10^{-7}$ cm²/bit, threshold LET $L_0=2.9$ MeV cm²/mg, $W=20$ MeV cm²/mg, and $s=2$. The dashed curve represents a step function with $L_{0.25}=13.6$ MeV cm²/mg.

The proton induced SEU cross sections are shown in Figure 8. It includes previous data [3] on devices from the same die. To complete the plot in Figure 8 for higher proton energies we use the heavy ion results (the Weibull fit in Figure 7) employing a simple model [4]. For the thickness of the sensitive volume we used $d=1.8\mu m$, estimated for the same device in reference [3]. Using eq. (6) in [4] with no fitting parameters we plot the full line in Figure 8. It overlaps the experimental results of low proton energies, giving us confidence in the model-extrapolation to high energies.

As can be seen from Figure 7, one needs heavy ion cross sections to extrapolate low energy protons SEU cross sections to high proton energies. Since these were not available for IDT 7006 and IDT 70V25, no attempt was made to calculate the inflight SEU rates of these devices.

IV. Calculated Rates

The special situation of several experiments under the same radiation conditions provides an excellent opportunity for validating the models which predict SEU rates. We present here three methods.

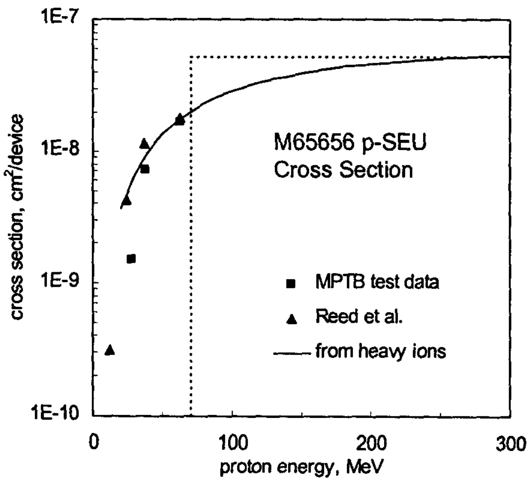


Fig. 8. The proton induced SEU cross sections for M65656. The experimental data at low proton energies are in agreement with the full curve calculated from heavy ion data. The dashed line represents an approximated step function at $E_{pc}=70$ MeV.

A. Using CREME96

Our rate calculations are based on ion flux spectra, calculated using CREME96 [5]. For the trapped protons we use the TRP module. Since the orbit exactly repeats itself each two revolutions we need to use a small number (2-10) of revolutions in CREME96 to prevent orbit shift. This way the flux will be correct since two revolutions take almost exactly 24 hours (CREME96 found for the double-orbit a period of 23.98 hours whereas the ephemeral files show 23.92 hours). The right input parameters are: (1) apogee at 39200 km, (2) perigee at 1220 km, (3) inclination of 63.6°, (4) we use the ascending node as starting point thus its initial longitude is taken as −16.41° (see Fig.1) and (5) the initial displacement from ascending node is 0°, (6) the perigee is at the extreme south latitude thus 'argument of perigee' is taken as +90°.

The MPTB board is shielded from space only by a thin (d_0=60 mil) aluminum plate (parallel to the device surfaces). All dual-port-board devices have in addition only the shielding of the casing. Much smaller flux arrives from inside the satellite and is taken as null.

To account for the varying thickness of shielding ($d_0/\cos\theta$ where θ is taken from the normal to the wall) we might prepare, for the CREME96 code, a table of thicknesses *vs* their weights. One way is to take equally separated angles (by $\Delta\theta$ in radians) between 0° and 90°. The weight for each ring is its solid-angle divided by 2π i.e. $\sin\theta\,\Delta\theta$. However, it is preferable to take more points the closer is θ to 90°, since there the incremental solid angle as well as the change in thickness are larger. For instance, the above $d_0/\cos\theta$ *vs* $\Delta(\cos\theta)$ can be taken in equal $x=\cos\theta$ spacing, i.e. n equally spaced x values from 1 down to a value close to 0.

Table 2: SEU rate calculations

A comparison between the observed SEU rates of M65656 and those calculated using several models. Rates are in SEUs/day-device.

ions	protons	heavy ions
observed	0.20 [a]	0.082 [b]
CREME96	0.25 [c]	0.069 [d]
simple model	0.23 [e]	0.110 [f]
FOM	- [g]	0.098 [h]

a. all events below 10,000 km.
Two. all events above 10,000 km.
Three. using PUP. Flux behind 60 mil Al board.
Four. using HUP. Flux behind the 60 mil Al board.
Five. step function for cross section. Integral flux behind the board.
Six. eq. (2).
Seven. the observed rate gives C=237 SEU/bit-day.
Eight. using the estimated C=115 SEU/bit-day.

The table we prepared for the TRANS module has n thicknesses of d_0/x (d_0=60 mil) and weights of $1/n$. We found that n=20 equally spaced points between x=0.975 and 0.025 gave excellent convergence.

Figure 9 shows the spectrum of protons in the orbit for MPTB. Due to contributions of high altitudes and the small shielding at low θ values there is high flux at low proton energies. The medium value is 16 MeV. This means a relatively high p-SEU rate for sensitive devices (those with a low critical charge) as discussed below.

Using the proton upset (PUP) module for this spectrum and the $\sigma_p(E_p)$ of Figure 8 gives a rate of 0.25 SEUs/day for a

M65656 device. This is in very good agreement with the observed rate of 0.20 SEUs per device-day below 10,000 km (see Section II.C and Table 2).

The calculations for heavy ions are similar. Figure 10 shows the differential LET flux-spectrum for a 60 mil wall and hemispherical radiation. The calculations employ the same table for the TRANS module used above for protons. It was found that this weighted averaging on the wall thickness is equivalent to taking a hemisphere with a constant thickness of 240 mil.

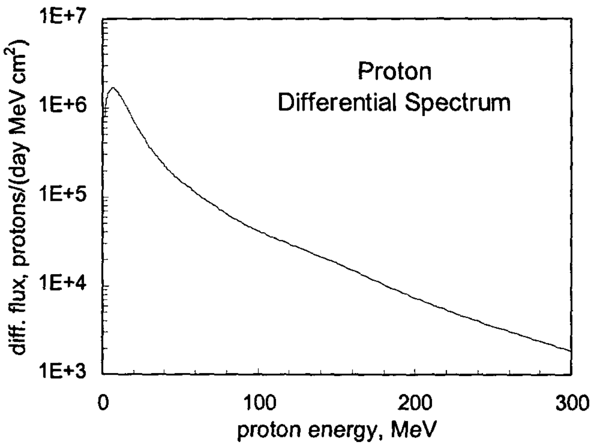


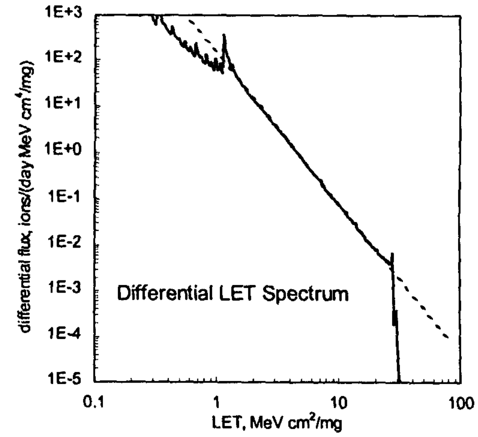
Fig. 9. The spectrum of trapped protons in the MPTB orbit. The calculations consider a wall of thickness of 60 mils parallel to the devices faces and a full shielding from the other side. Note the relatively high flux at low proton energies.

Fig. 10. The CREME96 LET spectrum of heavy ions in the MPTB orbit, for a wall of thickness of 60 mil (Al) parallel to the devices faces on one side (which is equivalent to a hemispherical shielding of 240 mil) and a full shielding on the other side. As shown by the dashed line, the flux is very precisely described by $f(L)=130L^{-3.22}$ for $1<L<28$ and zero otherwise (all in the units of the figure).

The heavy ion upset (HUP) module was used to calculate the rate with this flux, with the Weibull parameters of Figure 7, and with RPP dimensions ($a\times a\times c$) which correspond to the limiting cross section, 7.75μm × 7.75μm × 1.8μm, as input. The calculated rate is 0.069 SEU/device-day compared with the measured 0.082 SEU/device-day (Table 2). It is to be noted that the HUP module uses the averaged flux (Figure 10) for all directions. Here we know the angular dependence (due to the plane wall shielding) of the flux. We use this dependence in the model presented in the next section.

B. Using Simple Models

A simple calculation of the proton SEU rate will use a step function for the cross section (dotted line in Figure 8) and the integral proton fluence plotted in Figure 11. The limiting cross section value $\sigma_{pL}=5.3\times10^{-8}$ cm² is multiplied by the proton integral fluence (4.3×10^{6} p/cm²-day) at 70 MeV which is the energy of the step. This method gives a calculated rate



of 0.23 SEUs/device-day compared the measured rate of 0.20 SEUs/device-day (see Table 2).

A similar calculation for heavy ions using the normal incidence cross section (Figure 7) and the integral flux at $L_{0.25}$ is incorrect due to the angular dependence of the heavy ion cross section. Also, the use of the averaged flux (Figure 10) for all directions, the way we did in the previous section using HUP, is not rigorous since the flux behind the shielding plate is not isotropic. Usually the exact calculations are difficult to perform but here, since the devices are parallel to the shield plate both the flux and the cross section depend only on θ, the angle from the normal to the plane. This makes the calculations easier.

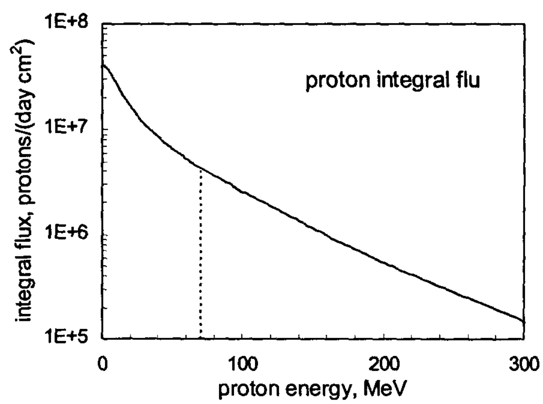


Fig. 11. The integral proton flux for Fig. 9. For a 'critical energy' of 70 MeV only about 10% of the protons have high enough cross section to be considered in the rate calculations.

Using CREME96 we have found that when increasing the thickness of the shielding, d_0, up to several hundred mils of aluminum, the shape of the flux *vs* LET of the GCR is retained. It is only exponentially attenuated. When taking d_0 in inches (rather than mils) the attenuation factor is simply 4 to the power of d_0. Thus using the expression in the caption of Figure 10, the differential flux may be approximated by

$$f(L,\cos\theta)\approx 4^{-d_0/\cos\theta}\times 183L^{-3.22} \quad \text{for } 1<L<28 \text{ MeVcm}^2/\text{mg} \ . \quad (1)$$

(d_0 is in inches). The cross section might be taken as $\sigma(L,\cos\theta)=\cos\theta\times\sigma(L/\cos\theta)$, from $\cos\theta=1$ down to about $\cos\theta\approx c/a$. $\sigma(L)$ is taken as the Weibull function in Figure 7. With the above limits for L and $\cos\theta$, the rate is found by

$$R = \int\int f(L,\cos\theta)\sigma(L,\cos\theta)dL\ d(-\cos\theta) \quad . \quad (2)$$

This calculation gives a rate of 0.110 SEUs/device-day compared with the measured rate of 0.082 SEUs/device-day (Table 2). Note that the CREME calculations yielded a smaller value of 0.069, still close to the experimental value since the wall is thin and taking averaged attenuation is not too bad.

Similar calculations to those presented here may be used for other MPTB parts.

C. Using the Figure Of Merit Model

The figure of merit (FOM) model was developed by Petersen [6] for fast estimation of the SEU rates R in orbit. An analytic study of the model is given in [7]. Each device has a FOM parameter calculated using either heavy ion cross section or p-SEU cross section. Using σ(LET) the parameter is given by $FOM=\sigma_{HL}/L_{0.25}^2$ where σ_{HL} is the limiting (saturation) heavy ion cross section and $L_{0.25}$ is the LET value for 25% of saturation. For M65656 we find $L_{0.25}$=13.6 MeVcm^2/mg by using the Weibull parameters of Figure 7 and eq. (2) of [6]. With $\sigma_{HL}=6\times10^{-7}$cm^2/bit (Figure 7) we find $FOM=3.24\times10^{-9}$. The SEU rate is given by $R=C\times FOM$ where C is an orbit parameter (good for all MPTB experiments facing the wall).

In order to find the value of C for the MPTB devices, for the heavy ion SEU rates, we note that the differential spectrum in Fig. 10 is very similar to that of galactic cosmic rays (Figure 1 in [7]) except for a scaling factor. We estimate the flux here to be 3.12 times weaker than for Figure 1 of [6] where a value of C=360 was found using CREME96. Thus here C=115 upsets/(bit-day). Multiplying this value by the *FOM* and 256k bits/device we find R=0.098 SEUs/device-day, close to the experimental value (see Table 2).

The C value for protons is harder to estimate due to the high flux of low energy protons. As shown above, M65656 has a relatively high 'critical' proton energy E_{pc}=70 MeV (Figure 8) and the p-SEU rate was in agreement with the integral flux at this value. Other devices might have lower E_{pc} values. The value which is in agreement with the above FOM and the observed p-SEU rates is C=237 upsets/(bit-day). We suggest using this value to estimate the p-SEU rates in other devices as well.

IV. Summary

1. Inflight data of SEU in the dual-port boards of the MPTB experiments were downloaded and analyzed.
2. The high number of SEUs, found east of South America, is due to the South Atlantic Anomaly.
3. The ion fluxes are calculated by considering a wall shielding and averaging over 2π directions.
4. The expected rates for M65656 are calculated using several methods and models.
5. Good agreement is found between the predicted and observed rates.

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